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FLEET MIX PLANNING IN THE U.S. COAST GUARD: ISSUES AND CHALLENGES FOR DSS*

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Fleet Mix Planning in the U.S. Coast Guard: Issues and Challenges for DSS*

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Abstract

Fleet mix planning in the U.S. Coast Guard involves determining a combination of naval assets best suited to meet the Coast Guard's future mission requirements while satisfying various resource constraints. In this paper, I describe the problem, and present and discuss certain challenges it raises in the field of decision support systems (DSS). The fleet mix planning problem is fairly unstructured, has a long-term planning horizon and impact, and there is uncertainty about future mission objectives and demand for the fleet's services. As such, I believe, it is a classical application suited to the use of DSS technology, according to accepted definitions of a DSS. However, an examination of DSS theory and technology reveals that current DSS theories and implementations do not adequately address this problem. Thus, the fleet mix planning problem raises several research challenges in the design and implementation of decision support systems. In this paper, I discuss the problem and these challenges in detail, and propose that fleet mix planning could be a useful benchmark problem for DSS.

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1 Introduction

This paper describes the fleet mix planning problem faced by the U.S. Coast Guard and has two objectives in doing so. The first is to discuss the various issues and challenges this problem raises for the field of decision support systems (DSS). The second is to pose the fleet mix planning problem as a benchmark problem for DSS. I will describe the problem and the problem environment in detail, and examine the theoretical and practical implications it has on decision support systems. I will argue that this is a classic DSS application according to widely accepted notions of a DSS, yet current theories and implementations of DSS prove insufficient in handling this problem. I will discuss the design and functional requirements this problem raises, and discuss recent prototype systems for fleet mix planning in the U.S. Coast Guard. The Coast Guard's version of this problem is not significantly different from a general fleet mix planning problem. However, in order to be precise and realistic, I will continue my discussion in the specific context of the Coast Guard's problem. From here onwards, the terms "problem" or "FMP problem" will refer to the U.S. Coast Guard's fleet mix planning problem.

Briefly, fleet mix planning involves the determination of a combination of assets (e.g., ships, helicopters) that is expected to "best" fulfill the fleet's mission objectives subject to constraints on the acquisition, deployment, and operation of the fleet. This combination of assets in a fleet is called a "fleet mix." The definition of a "best mix" or "good mix," and the constraints on a fleet, are both subjective and will be discussed further in the next section. It is easily seen that FMP decisions are made in a long-term planning horizon and have long-term impacts on the capability of the fleet to fulfill its mission objectives. Due to the cost of ships and other naval assets, fleet mix planning involves billions of dollars over several years.

Over the years, several definitions have been proposed to distinguish decision support systems from other kinds of information sytsems. For example, according to Scott-Morton [23], decision support systems are "interactive computer-based systems, which help decision-makers utilize *data* and *models* to solve unstructured problems." It is often argued that DSS are most useful for planning (strategic and tactical) rather than operational-level or highly structured problems. It is generally accepted that a DSS is distinguished from other computer-based systems in the fact that a) it can handle unstructured and semi-structured problems, b) it provides features for working both with models and with data, and c) it is interactive and has useful means for the presentation of data and models. I will show that the FMP problem has many characteristics of problems that decision support systems have been defined to handle. (I.e., it is unstructured, involves several models and lots of data, and requires non-trivial mechanisms for the presentation of data and models.) It then follows that a typical DSS would be able to solve the FMP problem, or else that the FMP problem is one that a DSS *ought* to be able to solve. And a DSS that works well for the FMP problem can well be considered a standard for decision support systems.

The rest of this paper is organized as follows. In the next section (§2) I discuss the fleet mix planning problem in some detail. I will attempt to illustrate the uncertaity and diversity in the measures of effectiveness, objectives and constraints, and exogenous data. In §3 I will discuss some modeling approaches to the FMP problem, and examine the role of modeling in this context. In §4 I will discuss the desirable characteristics of a DSS for fleet mix planning, examine the challenges that raises for DSS, and discuss some prototype systems that are being developed for fleet mix planning in the Coast Guard.

2 The Fleet Mix Planning Problem

Fleet mix planning in the U.S. Coast Guard (USCG) has been the subject of much recent research (see [3, 4, 17, 18, 20]). Similar problems have been analyzed previously in the context of rental car fleets [21], merchant shipping [6], and helicopter fleets [7, 25]. Subsets of the fleet mix problem have also received attention, e.g., deployment of a police patrol [10], and location of medical emergency services fleet [12]. As pointed out by Moore et al. [20], "The USCG's specific fleet mix problem is a genuine, real-world problem. It is of immediate, and high-priority concern to the USCG. Hundreds of millions of dollars will eventually be spent based on the USCG's recommendations ..." and "The general fleet mix problem is one that interests many organizations ... has given rise to an extensive operations research literature. There appear to be, however, no general, workable, and acceptable methods for fleet mix planning described in this literature." In this section, I will summarize the various objectives and constraints that define this problem, discuss the characteristics of the planning environment, and examine the implications of these on any DSS for this problem. Some of these items have been discussed in the references mentioned above, but they will be restated here for the sake of completeness. First, let us review some basic definitions and terminology that will be used in this paper.

2.1 Some Preliminary Definitions

Definition 1 *Asset*
An asset is a component of the fleet that (when suitably manned and equipped) is capable of, but not restricted to, functioning on its own to fulfill a part (or all) of some Coast Guard mission. Asset types of interest include patrol boats, cutters, helicopters and aircraft.

Definition 2 *Fleet Mix*
A fleet mix is a combination of assets, which states what kinds of assets, and how many, are included in the mix. If $\mathcal{A}$ is the set of asset types, then a fleet mix $\mathcal{F}$ is defined as

$$\mathcal{F} = \{\langle \alpha_i, n_i \rangle : \alpha_i \in \mathcal{A}, n_i \text{ integer}\}$$

where n_i is the number of assets of ype α_i. If $\mathcal{F}_\eta$ is one such set corresponding to a particular time period η, then the fleet mix in period η is written as

$$\mathcal{F}(\eta) = \langle \mathcal{F}_\eta, \eta \rangle$$

Definition 3 *Fleet Mix Plan*
A fleet mix plan is a statement, over a planning horizon, of the fleet mix at various time periods in the planning horizon. Thus, if $\mathcal{H}$ is the set of time periods in the planning horizon, and if $\mathcal{F}(\eta)$ is the fleet mix during the time period η, a fleet mix plan $\mathcal{P}$ for the horizon $\mathcal{H}$ is defined as

$$\mathcal{P} = \{\mathcal{F}(\eta) : \eta \in \mathcal{H}\}$$

Equivalently, a fleet mix plan states what kinds of assets, and how many, are included in the mix, and when each asset is acquired or retired.

Definition 4 *District*
A district is a unit of management in the Coast Guard [20]. An asset in the Coast Guard's fleet is assigned a homeport within its district of operation.

Definition 5 *Mission Needs*
The Coast Guard's mission needs are duties mandated by Congress, and are discussed in various Coast Guard publications (e.g., [15]). Currently, there are two primary missions: 1) ELT (Enforcement of Laws and Treaties, to minimize violations), and 2) SAR (Search and Rescue, to maximize rescues). There are also secondary missions such as fisheries and pollution control.

Definition 6 *Mission Demand*
The demand for a mission is a quantification of the mission-requirement expected to occur over a certain space-time combination. Geographically, demand may be expressed at the level of a district, or at a lower or a higher level of detail. Similarly, demand may be expressed over a month, year, or other unit of time.

The important thing to note about this is that there is significant ambiguity and disagreement between Coast Guard officers in the interpretation of these missions and on the actual mission demand, including for the primary missions [20]. Further, there is uncertainty regarding the future missions of the Coast Guard [3]. For example, there is discussion about privatization of certain search and rescue activities, and about legalization of certain drugs. Either of these events could significantly change the Coast Guard's missions (SAR and ELT, respectively). This reality is significant to any strategy or system for the FMP problem and leads us to our first observation about this problem.

Observation 1 *There is ambiguity and disagreement about the Coast Guard's current mission objectives, and there is uncertainty about its demand levels and future mission objectives.*

2.2 Measures of Fleet Mix Effectiveness

What is a good, and in particular best, fleet mix? How do we measure the effectiveness of a fleet mix? There is a fundamental distinction between the Coast Guard's SAR and ELT missions. The objective in ELT is to deter crime as well as respond to it. The presence of a force in an area is likely to reduce illegal activities in that area. Thus part of the ELT mission, deterrence, requires Coast Guard vessels to "just be there." However, *excellent performance as a deterrent might actually show a fleet to be a poor performer in intercepting and apprehending violators of laws and treaties.* Mere presence, or coverage of some areas, has little effect on the amount of SAR cases that happen. Instead, Coast Guard boats should be able to respond to calls for action as soon as possible, and then be able to perform the tasks required for a successful response. This distinction, and the deterrence paradox mentioned above, implies that several measures of effectiveness need to be combined to measure overall fleet effectiveness. No single measure of effectiveness will suffice, since it is always possible to create a scenario in which that measure is optimized but the real mission is not performed well. As another example, if the number of violators apprehended is the only measure, a force could create conditions that would encourage violations, and therefore increase the number apprehended. This leads us to the following observation.

Observation 2 *There are several kinds of measures of fleet mix effectiveness. While each of them is meaningful, it can be misleading if used alone. Several such measures must be examined simultaneously to get an accurate picture of the effectiveness of a fleet mix.*

It is useful to classify the various measures into three categories of cost-benefit measures of effectiveness: lifecycle costs, activity levels (i.e., potential activities / capabilities given the fleet mix), and mission performance (i.e., estimate of actual performance on primary Coast Guard missions).

2.2.1 Life cycle Costs

Since most assets in the fleet have a life cycle of about 30 years, it is important to consider the entire life cycle cost for a fleet, in addition to the likely benefits of having the fleet. There are standard methods for computing life cycle costs of major systems in the Coast Guard. Typically, the total cost is an aggregation of the costs of acquisition, operations, maintenance, personnel, facilities, disposal, and others. These costs are estimated, and suitably discounted, over the expected life cycle of each asset in the fleet.

2.2.2 Mission Performance Measures

Mission performance measures indicate the (expected) level of fulfilment of the specified mission objectives over a given period. While current mission objectives are quite clear, it is not so obvious how these should be measured. For example, the "number of lives saved" and the "number of illegal shipping activities intercepted" are plausible performance measures. However, a fleet mix that had a lower score on these measures just because it spent more time responding to "false" calls, compared to another mix that only responded to true calls, is not necessarily exhibiting inferior mission performance. Thus, one must also look at measures such as "percentage of total calls that were responded to in reasonable time." Thus, mission performance is an aggregate measure that includes at least 1) the number (and percentage) of lives saved, 2) number (and percentage) of illegal shipping activities intercepted, 3) the number seized, and 4) number of (SAR and ELT) calls responded in reasonable time. How should these measures be computed? Note that mission performance measures the actual or expected *response*, as well as the *outcome* of this response, to a demand for the fleet's services. Due to this interpretation, it is proposed [4] that mission performance would best be computed by simulating the fleet's performance over a period of time on several scenarios generated from suitable distributions of demand.

2.2.3 Activity Measures

While mission performance is concerned with responses and outcomes, it is also important to have measures of fleet *capabilities*, measures that are independent of particular demand distributions and response strategies. The activity measures indicate the potential activity levels and capabilities of a fleet under some assumptions of how the fleet is to be utilized. That is, they are concerned not with actual mission performance, but with activities (such as patrolling) that the fleet must perform to fulfil the mission. It is useful to classify these into two kinds of activity measures: those describing capabilities of individual ships, and those aggregating activities over an entire fleet.

The individual capability measures are 1) speeds (pursue, transit, escort, tow), 2) range, 3) endurance, 4) fuel consumption, and 5) crew size. These are relevant measures since they affect how well a ship can respond to a mission demand. (For example, a ship that can only carry 3 crew members may not be able to perform the task of boarding a vessel suspected of illegal activities.) They are also appealing since they can be measured with a higher degree of confidence than mission performance measures.

The aggregate activity measures are a) total number of patrol hours in each region, b) number of patrol hours in each region categorized by mission, c) total number of square miles covered by patrols in each region in a given period. These measures are relevant since in the absence of precise information about where and when which services would be required, a plausible performance estimate is the total amount of mission-related activities that can be performed by the fleet.

2.3 Objectives and Constraints

Now I will discuss the objectives and constraints underlying this problem. It is only a secondary purpose of this discussion to provide a clear statement of the FMP problem's objectives and constraints, as they are understood today. The primary purpose is to illustrate the diversity, complexity, and uncertainty, in these objectives and constraints, and to set the stage for a discussion of their implications.

The objective of fleet mix planning in the Coast Guard is to determine, for a given planning horizon, the best fleet mix plan to meet the Coast Guard's mission objectives subject to various constraints on the acquisition and operation of this fleet. Examining the definitions of a fleet mix and a fleet mix plan, it can be seen that this involves answering five basic questions:

1. *Which* types of assets should the Coast Guard acquire?
2. *How many* assets of each type should it acquire?
3. *When* should each asset be acquired and retired?
4. *How much* of an asset's operating time should be assigned to each mission within the district of its operation?
5. *Where* (i.e., to which homeport) should each asset be assigned?

The fourth question is relevant to the computation of expected mission performance for the different missions. The fifth question is relevant to determining whether a plan is consistent with existing or planned fixed facilities. Even though these last two questions are concerned with operational decisions and not part of the planning process *per se*, they would most likely have to be answered to determine the best plan.

If a DSS were to be used to develop an optimal fleet mix, what properties would we like this mix to have? Again, there are competing answers to this question. These include that the fleet mix should have the least cost, or best performance, or highest flexibility, as explained below.

1. Least Cost: The fleet mix with the lowest overall cost, subject to performance and other constraints. Even within this category, there are several definitions depending on how the overall cost is measured and how costs are aggregated over the planning horizon (next year's costs are usually most certain, later year's costs have higher variance). The optimal mix will depend on how the objective, i.e., total cost, is defined.

2. Best Performance: The fleet mix which best meets the Coast Guard's mission requirements, subject to budgetary and other constraints. Again, there are several definitions within this category depending on how mission performance is measured, how the measures of performance are compared and aggregated across various missions, and how they are aggregated over the entire planning horizon (next year's demands tend to be most certain, later year's demands have higher variance).

3. Most Flexibility: The fleet mix which is most flexible in its ability to meet changing mission requirements of the Coast Guard. It is argued that this is an important objective due to the uncertainty in missions and demands [3]. There are no readily acceptable measures of fleet flexibility, but some surrogate measures are discussed in §3.4.

There are several constraints that must be considered in developing solutions to the fleet mix problem. The most important of these are the budgetary (life cycle cost and cash flow) constraints, mission performance, and activity level constraints (these might be modeled either as constraints or introduced into an objective function). In addition, there are constraints on the total size of the fleet, and on the kinds of assets that can be a part of the fleet (e.g., because of pier facilities or trained personnel). And there are other constraints, but there have been few complete or deliberate attempts to list the constraints that a solution to this problem must satisfy. In reality these constraints are quite subjective and "soft," due to which there are several possibilities that must be examined. For example, if a fleet mix which has excellent cost and performance measures is infeasible because of current pier facilities, should the Coast Guard select a less desirable mix or should it invest in upgrading the pier facilities? Are budget constraints fairly tight or could higher expenditures be authorized by the promise of better performance? What is the certainty of future budget estimates given the state of the economy, constrained government spending, and the government budgeting process?

What is important to note in the paragraphs above is that there is not a unique measure of how good a fleet mix is, nor is there a widely accepted set of constraints underlying the problem. Apart from that, there are several points of view on these issues, since there are several groups interested in, and affected by, the problem. To be useful, therefore, a DSS for fleet mix planning would have to allow for the representation and analysis of these multiple viewpoints. Of course, several models and much of the data would be common to several viewpoints. The DSS should have an integrated database and an integrated modelbase that allows a user to work with any, or several, of these viewpoints. Without going into further details, it is safe to state that

Observation 3 *The constraints underlying the FMP problem are subjective. There is no single or dominant point of view on the set of constraints that should be considered, or on exactly what should be optimized, to get an optimal fleet mix.*

2.4 Data Requirements and Availability

It should be obvious from the above discussion, and particularly due to Observations 1–3, that the data requirements for a proper analysis of the FMP problem are enormous. There are a lot of factors, exogenous to the problem, for which data must be gathered. Demand for the Coast Guard's services for future time periods is an input to the FMP problem, and itself is a function of various parameters such as inflation rates, income levels, as well as government policies and market forces. The capabilities (including speeds, fuel consumption, stability) of various assets to operate under different environmental conditions must be estimated before cost and performance measures can be computed for them. A lot of oceonographic and meteorological data collected by the Coast Guard is relevant to this issue. While plenty of data relevant to the FMP problem is available, much that is required is not. In addition, some of the available data is of questionable accuracy. Since most of the data requirements span over a long-term planning horizon, it is not surprising that much of the data consists of predictions, estimates, guesses, and even arbitrary numbers. It is important to recognize this since the results of any analysis are only as good as the inputs to the process. To summarize,

Observation 4 *There is considerable uncertainty and inaccuracy in the exogenous data relevant to the fleet mix planning problem; this must be taken into account during any analysis of the problem either by examining multiple and representative scenarios or by incorporating the uncertainty into the analysis process.*

2.5 Characteristics and Implications

Why would a group involved in fleet mix planning want to use a DSS? The obvious answer may seem, to determine the best fleet mix. However, in practice, the fleet mix problem does not simply require an answer to the question "What is the best fleet mix?" One, Coast Guard officers recommending a particular fleet mix are required to defend this recommendation in front of Congressional bodies, or groups of their own colleagues, whose members may have recommendations of their own. A recommendation by the Coast Guard of the "best" fleet mix would not have much chance of being approved if the panel making that recommendation could not make a cogent and convincing argument in favor of this mix. It is, then, a major function of the DSS to help in the construction of such an argument.[1] So, a relevant question is "How do I support this recommendation?" Two, it is often the case that the Coast Guard wishes to include, *a priori*, a certain set of assets in the fleet mix. It is then relevant to examine the circumstances under which that would be an optimal or reasonable decision (and then to examine how likely, or how significant, those circumstances are). Again it is expected that a DSS should prove useful in performing this analysis. Thus, another relevant question is "Under what circumstances is this recommendation justifiable (or the best one)?" These questions are particularly relevant because of the uncertainty, discussed earlier in this section, in the constraints and measures of effectiveness. To summarize, we have

Observation 5 *Broadly speaking, there are three ways in which a DSS for fleet mix planning would be used: 1) to determine the best fleet mix, 2) to develop an argument to support a proposed mix, and 3) to identify circumstances under which a proposed mix would be justifiable.*

The decision to acquire a ship is typically irreversible and of a long-term impact—once ships are built and bought, they essentially remain with the fleet for a few decades. However, not much is known, at the time the decision is made, about the operational environment that will prevail during this time period. As pointed out by Bradley et al. [6] in the context of a very similar problem, it is important to analyze the problem under various data scenarios, perform lots of sensitivity analysis, and select a solution that is not necessarily optimal in any one scenario but that is close to optimal in a wide range of data scenarios. The FMP problem is semi-structured at best, and one where analytical models are hard to formulate, solve, and get users' acceptance on. The problem gets even more complicated when we consider the interactions between mission tasks (in principle, an asset could perform more than one task at a time), resource-sharing between districts (assets in the western border of one district probably could respond to demand in the adjacent eastern sector of another district), and interactions between assets (the synergy effect between different asset types: a group of cutters may become more effective if combined with a helicopter [20]). Each of these factors would affect the performance score of a fleet mix, and therefore the selection of an optimal mix. Therefore, a DSS should have features that allow users not only to analyze alternative fleet mixes under a set of assumptions, but also to examine the consequences

[1] This view is consistent with, and lends credence to, the argumentation theory of DSS [19] which states that a DSS is a tool for helping the decision-maker develop a convincing argument for, or against, a particular course of action.

of making different assumptions, of considering different data scenarios, and of using different models. It is clear that this requires innovative user interface, data management, and model management features, and a "workbench-level integration" of various tools. I will discuss that further in §4.

3 Fleet Mix Planning: Perspectives and Models

The purpose of this section is to illustrate the number and diversity of models that are relevant to the FMP problem. Some of these models, and others, have been discussed in [3]. The goal here is not to be exhaustive, but to give reasonable evidence about the complexity and diversity of the problem. There are several ways of looking at, and developing models of, the FMP problem. There are different models for different parts of the problem, where some models provide solutions that are inputs to other models. In some cases there are several alternative models for the same part of the problem. These represent different assumptions, different points of view, or simply different perspectives on fleet mix planning. Further, these models belong to different modeling paradigms including optimization, goal programming, simulation and utility modeling, which until now have not been integrated in decision support systems. Ideally, a user of an FMP DSS should be able to work with all these models in a single or integrated system.

3.1 Capital Budgeting

The fleet mix problem might be thought of as a capital budgeting problem ([13], pp. 13), where the task is to determine a set of new assets that can be obtained using a given capital so as maximize the performance of the fleet. Assume that there are n assets available for acquisition, with asset j $(= 1, \ldots, n)$ having a *present value* of c_j, and requiring an investment of a_{ij} dollars in time period i $(= 1, \ldots, m)$. Assume also that the acquisition budget for period i is A_i. Let x_j denote the the number of assets acquired of type j. The problem then is to determine values for all x_j's to maximize the total present value $(\sum_j c_j x_j)$, subject to the budget constraint $(\sum_j a_{ij} x_j \leq A_i)$ for each time period.

There are several extensions to this simple model. One extension is obtained by considering all cost categories (instead of only acquisition cost) and the overall budget in each time period. A second is to select a fleet mix that minimizes the total life-cycle cost, with performance or mission requirements as the constraints. A third is to maximize the expected performance (i.e., to select a fleet with the best functional capabilities) subject to cost constraints. Of course, the usefulness of this model depends on how well the future Coast Guard budget is predicted and how well the present value (including expected performance and lifecycle costs) of assets is estimated. To allow for the inaccuracies in these parameters, it is possible to treat various parameters as random variables and obtain a stochastic optimization model.

3.2 Multi-Period, Multi-Item Inventory Management

Even if the question of *how many* assets to acquire has been answered, there is the question of *when* to acquire and to retire specific assets. Recall from §2 that a fleet mix plan states the fleet mix for each time period. Given a fleet mix in period t, which assets should be acquired (or retired) to achieve the desired mix in period $t+1$? Is it always a good idea to have the "optimal" mix, or might it be better to have an overcapacity (or undercapacity) in some periods? This problem can be thought of as a multi-period inventory management problem. Assuming that we know the optimal mix for each time period, and that there is an initial inventory (fleet mix), the problem is to determine a feasible acquisition (and retirement) plan for all the future time periods so that the fleet mix in each time period is as close to optimal as possible. The plan should be feasible in the sense that assets are held for a reasonable number of years, and there is no sudden retirement or acquisition of a large number of assets.

Ideally, in each period, the Coast Guard should have the optimal mix for that period. However, this might not be possible or even desirable, since once an asset is acquired it must be held for at least a certain number of time periods; it cannot be discarded just because it is not required in the next time period. There is a basic tradeoff between acquiring assets early (so that demand is fulfilled) and acquiring them too late (so that there is no excess inventory in certain periods). The simple model would assume no setup costs, fixed lead time, and deterministic demand. The issues to be considered include holding costs (early acquisition of assets implies higher personnel and maintenance costs), cash flow (early acquisition implies earlier outflows of cash), demand (late acquisition may lead to unsatisfied demand in some period), and operations costs (late retirement leads to higher operating costs even though it might reduce the need for new assets). The constraints are the requirements for the fleet's services, thresholds for fulfillment of demand, and constraints on the acquisition schedule.

Again, several enhancements can be made to this simple model. One is to allow lost sales, i.e., to allow the fleet mix to be below the level required to meet demand in a certain period. This would require imputing a "dollar value" to the lost sales. Another is to model the setup cost of orders, which means it might be cheaper to order several ships in one order even if that leads to excess inventory in some period. Other extensions include stochastic lead times (true in practice) and stochastic demand (true in practice). Thus the question of *when* to add and remove assets from the fleet can require fairly sophisticated modeling if it were to be answered with careful analysis.

3.3 Facilities Location (Homeport Assignment)

Assume that we have a fleet mix plan $\mathcal{P}$ and a schedule for achieving this plan. Which assets should be assigned to which homeports in each district? The question is important since the homeport location of an asset determines which areas it will be able to serve and which kinds of missions it will perform. Assume that there is a demand scenario $\mathcal{D}$ which predicts the demand (such as number and types of search and rescue cases) likely to occur in various geographical units, in each period. Assume also a mission statement $\mathcal{M}$ of the fleet's objectives with respect to the demand for its services. While the demand is disaggregated geographically, the plan $\mathcal{P}$ only tells us the aggregate number of available vessels of each type. Thus, another fundamental problem is to determine the allocation of these vessels (resources) to the various geographical units, so as to optimally satisfy $\mathcal{M}$. The problem of locating the vessels comprising the fleet can be viewed as a *generalized* facilities (or plants) location problem. The *single* capacitated plant location model ([13], pp. 18) determines the optimal location out of a set of m candidate locations (geographical units) for a plant (vessel) that produces a particular commodity (service, such as search and rescue) and has a finite capacity. It assumes that there are n customers (geographical units) with demand b_j for service j, with cost c_{ik} of serving customer k from plant i. In the fleet mix context, this model can be generalized to include multiple plants (assets) and multiple commodities (missions).

3.4 Fleet Flexibility

It is argued in [3] that given the uncertainty in the future mission needs and demand levels, it is a good policy to develop a fleet mix that is most *flexible*. Such a mix would be minimally affected by a change in the mission requirements or by changes in demand patterns. This seems to be a rational policy in the face of the observations made in §2. The issue then is how to measure fleet flexibility and how to determine the extent to which a mix would be affected by changes in the assumptions under which it was developed. A surrogate measure for fleet flexibility, called *diversity*, was developed in [3] with the rationale that a more diverse mix (more types of assets) was likely to be more flexible than one with less diversity (more assets of the same type). A measure of diversity, D, was defined as

$$D = \prod_{i=1}^{M}(1 + n_i)^{\alpha_i}$$

where M is the number of asset types, n_i is the number of assets of type i, and α_i is a measure of relative flexibility of an asset of type i. The objective was to determine values for the n_i's so as to maximize fleet diversity under the constraint that the total number of assets, N, is fixed ($\sum_{i=1}^{M} n_i = N$). It was shown that diversity is maximized when $(1 + n_i)/\alpha_i = (1 + n_j)/\alpha_j$, and that the optimal values for n_i are given by

$$n_i^* = (M + N)\frac{\alpha_i}{\sum_{i=1}^{M}\alpha_i} - 1$$

This is a simple approach but one where the results are easy to compute and to explain. There are several extensions to make this approach more realistic. One extension is to constrain the total *cost* of the fleet, instead of (or in addition to) constraining the total *number* of assets in the fleet. A second is to define a flexibility index β_i that measures asset flexibility *relative to the cost* of the asset. A third is to develop a multi-period formulation of this model where the optimal diversity is examined with budget constraints for each time period. Other variations are possible, but once again we see that given a certain way of looking at the problem, various models can be developed ranging from ones that are simple and less realistic to ones that are more realistic but also more complicated.

3.5 Discussion

There are several other models that are relevant to other parts of the problem. An important set includes multi-attribute utility models that provide a way to combine and compare diverse factors such as SAR mission performance, ELT mission performance, and cost. These factors are measured in completely different units. and the multi-attribute utility models provide a systematic method to tradeoff, e.g., lives saved with amount of drugs interdicted. Another set of models includes forecasting models to forecast demands for future time periods depending on historical demand patterns and various assumptions about the future. Fleet utilization models can be developed to determine optimal allocations of assets to specific missions in specific geographical areas. Simulation models can be used to evaluate fleet performance under various operating assumptions. Life cycle cost models, currently being used in the Coast Guard, can be used to examine costs of various proposed fleet mixes. Multi-objective and goal programming models can be used to develop or evaluate proposed fleet mixes while considering several objectives, possibly conflicting, simultaneously. Stochastic modeling techniques could be useful in handling some of the uncertainties discussed earlier.

The above discussion illustrates that several models, from various modeling paradigms, are relevant to parts of the fleet mix planning problem. It is, therefore, desirable to have a system where an analyst can work with several of these models and exchange information between models or examine the consequences of using one set of models versus using another. Given the lack of clear mission objectives and constraints, and the inaccuracy and non-availability of data, modeling may seem to be a futile exercise and one might ask "Why model at all?" In my view, models and modeling become even more relevant in this situation. "The purpose of modeling is not just to 'get an answer,' but also to develop sharper insights into, and understanding of, the problem itself, by examining various facets of it, and by exploring alternative ways of looking at the problem" [2]. "A model allows one to keep track of a line of thought, focusing attention on the important parts of the problem" [22] and "the point of making models is to be able to bring a measure of order to our experiences and observations" [9]. Clearly, modeling is useful in the FMP problem but it requires a decision support system that is radically different from the kinds of DSS that are available or being designed today. Let us go on to examine some of the desirable characteristics of such a system.

4 DSS for Fleet Mix Planning

In this section, I discuss desirable characteristics of a DSS for fleet mix planning, and examine some of the challenges in the design, implementation and use of decision support systems, that are brought to the fore by the FMP problem. The purpose is not necessarily to present *new* challenges—many of these have been recognized and researched, and even partially overcome—rather it is to show that the FMP problem raises all of these challenges, and therefore that it could be a useful benchmark problem for DSS research. Following that discussion, I describe some ongoing efforts in the development of systems for supporting fleet mix planning in the U.S. Coast Guard.

4.1 Required Functionality and Challenges for DSS

A DSS is generally considered as consisting of three main software modules—model management, data management, and dialog management (or user interface) [8, 24]. Significant progress has been made in the data management and user interface components, and more recently in the model management component. The FMP problem raises challenges within each of these components, but particularly in the model management component. It calls for the development of languages and systems in which users can conveniently work with several different types of models. It requires features not only for in-depth analysis using a set of models, but for comparing various alternative sets of models under various data scenarios. Further, recalling Observation 5, it calls for a system which integrates model management and data management capabilities with capabilities for report generation, documentation, and argumentation, in a manner that is informally termed "workbench-level integration." The 8 desirable characteristics of modeling systems outlined by Geoffrion [14] are particularly relevant to the FMP problem. I will not repeat those here, but will discuss specific features that a DSS for fleet mix planning should have. These features are, to a large extent, dictated by the process and role of modeling in fleet mix planning.

1. Model management: The role of models in a long-term planning environment (such as in fleet mix planning) is clearly articulated by Bisschop and Meeraus [5]. The following statements from this paper strongly apply to the FMP problem.

    "[Models] are used as a framework for analysis, for data collection, and for discussion. They are created to improve one's conceptual understanding of the problem. If several decision-makers and/or institutions are involved in a final decision or set of recommendations, models can be used as neutral moderators to guide the discussions. Different viewpoints can be tested and examined. In such an environment the actual values of model results are not so important, but the relative values resulting from testing different scenarios are of interest. The model is a learning device, and should never be expected to produce final decisions."

Some of the specific challenges that the FMP problem raises in model management are:

(a) Modeling languages and model representation: A DSS for the FMP problem clearly requires modeling languages that allow users to represent and exercise models from several different paradigms within an integrated software sytsem. None of the systems available today meet this requirement, even though considerable progress has been made recently in the design and implementation of modeling languages. The design of formal languages that can represent and reason with a wide variety of model types is still a major challenge in model management and DSS research.

(b) Model integration: The presence of several alternative models for subsets of the problem raises the need for the integration of these models. Model integration is recognized to be an important and challenging problem, and it is more so when these models are from different paradigms. What features should modeling languages have to facilitate such integration of models? How should these features be implemented?

(c) Reasoning with assumptions and version management: The lack of agreement on objectives, constraints and effectiveness measures, implies that different models will be developed based on different or changing views on these issues. Current languages and systems have few features for adequately representing, providing convenient access to, and examining the consequences of changes in, assumptions. "As modeling is a dynamic process in a planning environment, it becomes an horrendous task to document the many versions of each model, especially when they are large" [5]. That raises the need for the systematic representation and management of multiple model versions. Some questions that a DSS should help answer are: Which versions are in conflict? Which ones are obsolete? What are the differences between two versions? Which versions are consistent (or inconsistent) with a given set of assumptions?

(d) Post-solution analysis: It is useful, but hardly sufficient, in the FMP problem to develop, implement, execute, and perform sensitivity analysis on, a set of models and problem data. Post-solution analysis should determine not only how robust a particular solution is to some input data, but also how robust and reliable are the models (a "model-level sensitivity analysis") that the solution is based on, given the variance in objectives, constraints, and effectiveness measures. What kinds of features would be useful in the support of such analysis? Perhaps a new set of techniques and features, beyond those available in current systems, must be implemented to meet the requirements of fleet mix planning. Some such techniques—under the name of "candle lighting analysis"—are discussed in [16], but post-solution analysis remains a vastly under-researched area in decision support systems.

2. Data management: The basic issues in data management (of storage, retrieval and update) are handled well in DSS, but the FMP problem raises other issues, many of which have been the subject of DSS research for several years. How should large data sets, often containing data of doubtful reliability, be communicated to users in a meaningful manner? What additional information about data (other than the value) needs to be stored in decision support systems so that users are aware of its limitations?

3. User interface: The FMP problem creates several opportunities for innovative ideas in user interface design and implementation. Due to the large amounts of —and uncertainty in—data, and the large variety of models, it requires non-conventional methods for the representation of models, exogenous data and model solutions, and perhaps a new way of thinking about user interfaces (see, e.g., the paper by C.V. Jones in this book). It provides an opportunity to prove the usefulness of ideas in hypertext [11], visual representations, and direct manipulation interfaces.

4. Distributed computing: Data relevant to a fleet mix planning DSS is currently stored in several different databases that exist on different machines and use different database management software. Similarly, models for subsets of the FMP problem will likely be developed and used by different

individuals or groups working in different locations and representing different viewpoints and assumptions. In fact, components of the same model might be developed in such a fragmented manner and must be brought together. In general, a DSS for fleet mix planning will probably involve distributed and networked computing. It would also require support for multiple viewpoint analysis and distributed model development. That is an area that is virtually unexplored in implemented decision support systems.

5. Organizational issues: The FMP problem also raises several organizational issues, particularly in the understanding and acceptance of decision support systems. DSS are a fairly new technology in the Coast Guard. In addition, due to the fact that there are multiple players in the process of fleet mix planning, it is likely that there would be opposition to the use of models and decision support systems. Of course, as mentioned earlier, if they are used, decision support systems can act as neutral moderators between the various groups involved in this process.

6. DSS evaluation: Even if decision support systems for fleet mix planning were available, how would one measure the effectiveness of such systems, given the long term impact of the decisions and the uncertainty in the information on which the decisions are based? More importantly, how should *alternative* systems for fleet mix planning be used? Given a choice between two such systems, which one should a decision-maker select? Again, fleet mix planning offers a useful case for the testing of various theories and methods for DSS evaluation.

4.2 Prototype Systems

Moore, Kimbrough and Monaghan [20] discuss a decision support system being developed for the Coast Guard's FMP problem. This system is based on the "balance sheet approach" to fleet mix planning [3]. The idea is to to represent key, measurable, fleet attributes in a DSS and to provide useful features to allow for the access, comparison and exploration of several attributes across several proposed mixes. The system is implemented in *Quintus MacProlog* (for modeling) combined with an *Oracle* database (for data management) and a graphical, hypertext-based, user interface. It allows users to examine the "supply" and "demand," given a particular fleet mix and demand scenario. It aims to allow analysts to make different sets of assumptions to arrive at demand and supply values, to record and retrieve the assumptions and comments in a disciplined manner, and to conveniently compute and present the statistics of interest. The system's user interface and data presentation capabilities are designed in a manner that one could do useful work with the system with little prior training on how to use it. The hypertext features give users complete—yet discretionary—access to data, results, and assumptions. Another interesting feature is one where "reports" generated by the system can be directly compiled and printed using the LaTeX document typesetting system. The system has found ready acceptance in the Coast Guard. It is being used because of its innovative feature set and because it improves the Coast Guard's process of making asset acquisition decisions.

There has been considerable other research in developing modeling and decision support systems for the Coast Guard. A simulation based system for performance evaluation of a fleet mix is under development [4]. This system computes measures of fleet performance, under varying assumptions about its operational environment, over various demand scenarios. The model management system TEFA, and the DSS shell MAX which TEFA is a part of, have been discussed previously in [17] and [2]. TEFA is a general purpose model management system which facilitates the rapid creation, documentation, and exercise of mathematical models, and has useful features for the communication and explanation of models and model solutions. It uses an algebraic modeling language for the representation of models, and a generalized hypertext interface to present results and reports. While TEFA is not used directly for fleet mix planning, experience with TEFA has proven the usefulness of an algebraic language and a hypertext interface in a model management and decision support system. This should hold as well for a FMP DSS. Experience with TEFA has also proven the usefulness of the embedded langauges technique [1] which is the basis of its design. The embedded langauges technique provides a systematic way to represent and reason about modeling elements, including models, modeling variables, and data scenarios. It also provides a systematic way to integrate multiple lagnuages in a model management system. Because of the diversity of models relevant to the FMP problem, and because of the need to represent vast amounts of information about these models, both of these features are expected to be valuable in a fleet mix planning DSS.

5 Conclusions

This paper has described the U.S. Coast Guard's fleet mix planning problem and has presented this problem as a benchmark problem for decision support systems. It has also attempted to raise certain challenges to the development of a DSS for fleet mix planning. Of course, these challenges have been recognized and discussed previously, and there are other problems that share similar characteristics as well. The fleet mix planning problem is an effective illustration of semi-structured long-range planning problems characterized by inadequately defined issues and considerable uncertainty. The motivation in writing this paper has been that it will provide researchers with a single problem that is rich in challenges in a large set of areas of DSS research—including model management, user interface, software integration, distributed computing, organizational issues, and DSS evaluation. Problems such as fleet mix planning provide fertile ground for testing ideas and alternative approaches in all of these areas of research. Finally, a successful and effective DSS for fleet mix planning would be an outstanding example of a decision support system.

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